



Analyses of winter circulation types and their impacts on haze pollution in Beijing

Jianjun He^{a,*}, Sunling Gong^a, Chunhong Zhou^a, Shuhua Lu^a, Lin Wu^{b,**}, Ying Chen^c, Ye Yu^d, Suping Zhao^d, Lijuan Yu^e, Chengmei Yin^e

^a State Key Laboratory of Severe Weather & Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, Beijing, 100081, China

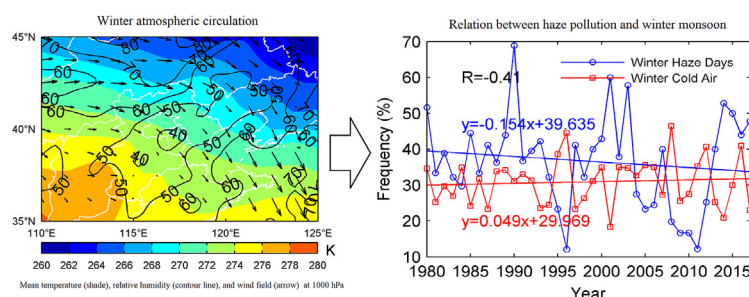
^b The College of Environmental Science & Engineering, Nankai University, Tianjin, 300071, China

^c Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK

^d Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, 730000, China

^e Jinan Meteorological Bureau, Jinan, 250002, China

GRAPHICAL ABSTRACT



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ABSTRACT

To better understand the interannual variation of winter haze pollution, this paper investigates winter circulation types and their impacts on local meteorological conditions and haze pollution during 38 winters from 1980 to 2017 in Beijing. Circulation types were classified by T-mode principal component analysis combined with the K-means cluster method using European Centre for Medium-range Weather Forecasts ERA-interim sea level pressure data. The results can significantly distinguish the cold air process, a degeneration of cold air, and stagnant weather. The cold air process over Beijing was accompanied by a low temperature, high relative humidity, large pressure gradient and near-surface wind speed, and deep mixing layer. The cold air process facilitated pollutant dispersion and transport to the outside (such as East China, Bohai Sea, and Yellow Sea) and formed low PM_{2.5} concentrations and low frequencies of haze days. In contrast, the local meteorology and haze pollution were almost the inverse for stagnant weather. The local meteorological conditions and haze pollution for the degeneration of cold air are between the previous circulation types. Considering PM_{2.5} observation during 2010–2017, the occurrence frequency of cold air was low in the recent winters of 2013, 2014 and 2017, and resulted in severe PM_{2.5} pollution. High frequency of stagnant weather (48.4%) was one of the reasons that haze pollution reached 37% during 38 winters from 1980 to 2017 over Beijing. The time series of haze frequency was negatively correlated with that of cold air frequency. Winter haze pollution was affected by climate change over Beijing. During 38 winters from 1980 to 2017, a decreased trend of haze days was found, which was partly

* Corresponding author.

** Corresponding author.

E-mail addresses: hejianjun@cam.gov.cn (J. He), envwu@vip.qq.com (L. Wu).

related to an increased trend of cold air frequency. However, the trends of haze days and cold air in Beijing were not significant based on regression analysis.

1. Introduction

Haze is defined as large amounts of fine dry particles floating in the atmosphere that result in low visibility (less than 10 km) and turbid air. It is a weather phenomenon and a natural weather disaster (Zhang et al., 2013). With rapid economic development, haze pollution has occurred frequently and has attracted attention from government, the public, and researchers. Severe haze, which is mainly caused by serious aerosol pollution, is not a completely natural phenomenon in China (Zhang et al., 2013). And it also affects weather, such as cloud and precipitation (Guo et al., 2016; Li et al., 2017). The formation of haze decreases atmospheric visibility, affects the production and lives of people, and has an adverse impact on human health (An et al., 2015). Unfortunately, at least 30% of the area and nearly 800 million people in China are affected by different degrees of haze (Che et al., 2009). There were relatively few annual haze days in the 1960s, but they increased sharply in the 1970s, remained stable to 1995, and then increased from 1995 to 2012 in North China (Chen and Wang, 2015).

Understanding the formation mechanisms of haze is very important for haze prevention.

Pollutant emission and meteorological conditions are two key factors for haze pollution, and high pollutant emission is the primary cause. According to the China Statistical Yearbook, the emission of sulfur dioxide, nitrogen oxide and dust reached 1.86×10^7 , 1.85×10^7 , and 1.54×10^7 tons, respectively, in 2015 (<http://www.stats.gov.cn/tjsj/ndsj/2016/indexch.htm>). Emission statistic has some uncertainties, and the uncertainty of emission is a main reason for the bias of air quality simulation (Chen et al., 2016). Meteorological conditions are another important factor for haze pollution. Meteorological parameters, such as temperature, relative humidity, wind speed, and boundary layer height, were significantly correlated with pollutant concentrations in most Chinese cities and explained more than 70% of the variance of daily average pollutant concentrations (He et al., 2017a). In January 2013, a persistent severe haze event occurred over eastern China. Unusual meteorological conditions were responsible for this persistent severe haze event (Zhang et al., 2014). The long term trend of haze

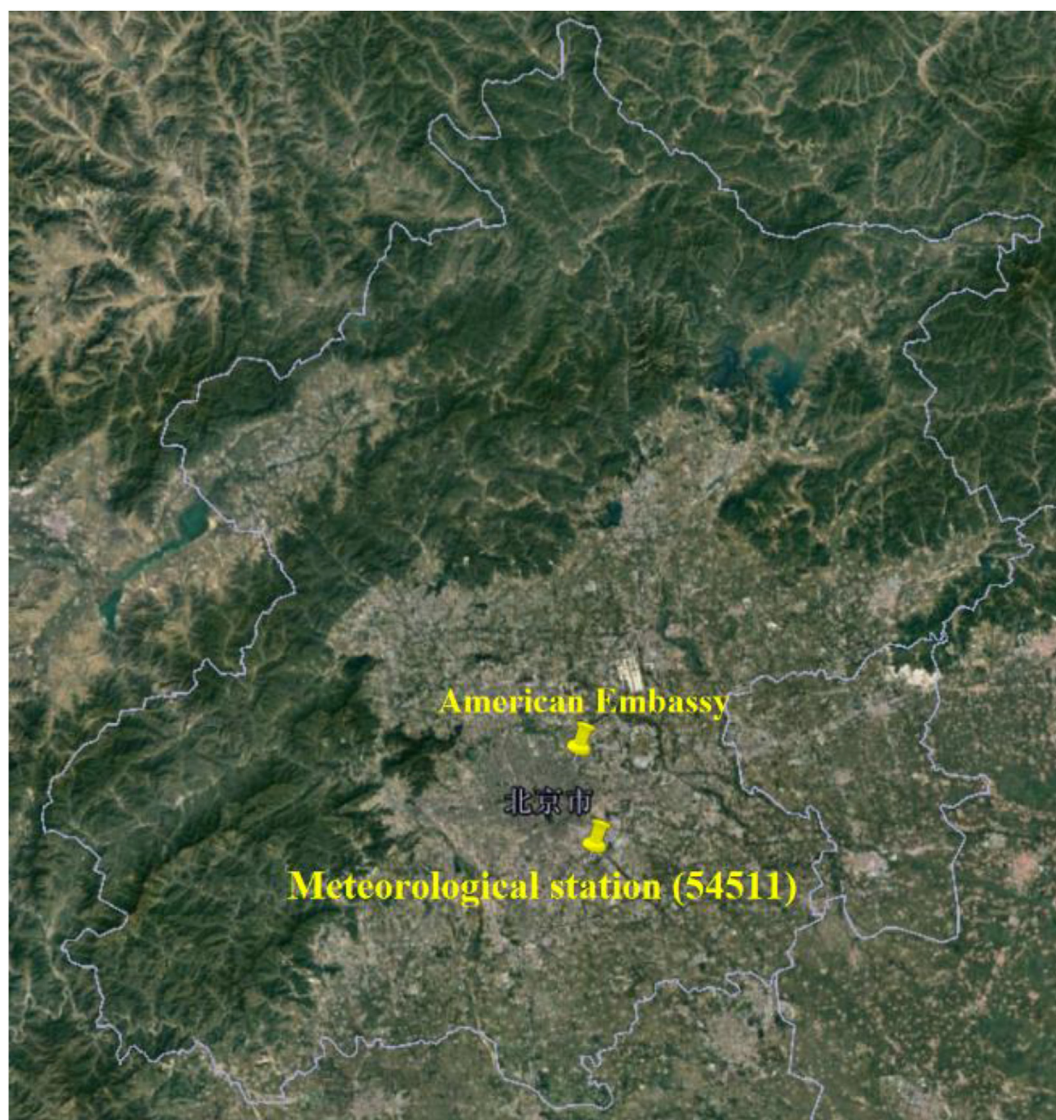


Fig. 1. The location of air quality monitoring stations (American Embassy) and meteorological station.

depended on region and season. Haze showed decreasing trends during 30 winters from 1981 to 2010, while summertime haze displayed continuous increasing trends, and obvious regional difference of haze trends was detected in southern Hebei province (Fu et al., 2014). The weakening of near-surface winds during 1985–2005 caused the increase in winter haze days over eastern China (Yang et al., 2016). At different spatial scales, meteorological conditions can be divided into a large-scale circulation type and local meteorological conditions. The circulation type governs local meteorological conditions and is effective in the identification of haze pollution (Oanh et al., 2005); it is the main factor driving the day-to-day variations in pollutant concentrations (Lee et al., 2012). Although many studies have investigated the relation between circulation type and haze pollution (or air quality) (Demuzere et al., 2009; He et al., 2016a, 2017a; Jiang et al., 2014; Jiang et al., 2017; Lee et al., 2012; Oanh et al., 2005; Pearce et al., 2011; Zhang et al., 2012), this relation can also vary with time, location and pollutants (Jiang et al., 2017).

Beijing, as the capital of China, has frequently suffered severe haze pollution in winter. Many pollutant emission sources surround Beijing, and local vehicle emissions, special terrain and meteorological conditions are the main reasons for haze pollution in Beijing (He et al., 2016b). Horizontal transport of pollutants, which is affected by atmospheric circulation, may be the most important factor determining the air quality of Beijing (Miao et al., 2017). Some studies have focused on the relation between circulation types and air pollution in Beijing and the surrounding region (Chen et al., 2008, 2009; Li et al., 2012; Meng and Cheng, 2002; Miao et al., 2017; Zhang et al., 2012). However, few studies have analysed the long-term winter circulation types by using an objective method or their relationships with haze pollution in Beijing and surrounding regions. This article extends previous work (He et al., 2017b) by using long-term data to investigate the thermal and dynamical characteristics of circulation types and their impacts on local meteorological conditions and haze pollution over Beijing. Because haze pollution is most severe in winter, this paper focuses on the winter circulation type. The results can help us understand the formation and change of haze pollution and are useful for haze forecasting and prevention over Beijing and similar areas.

2. Data and method

2.1. Meteorological data

The European Centre for Medium-range Weather Forecasts (ECMWF) ERA-interim reanalysis data (<https://www.ecmwf.int/en/research/climate-reanalysis/era-interim>) for 38 winters (December to February) from 1980 to 2017 were used in this study. The spatial and temporal resolutions of ECMWF ERA-interim data are 0.25° and 6 h (i.e., 08:00, 14:00, 20:00, 02:00 local standard time every day), respectively. Based on previous studies (He et al., 2017b; Jiang et al., 2017; Zhang et al., 2012), Sea level pressure (SLP) for the area of 110°E–125°E/35°N–45°N was used to identify circulation type. Temperature and dew point temperature at 850 hPa, 700 hPa, and 500 hPa from the ECMWF ERA-interim reanalysis data were used to calculate the K index, which represents atmospheric thermal unstable capacity in the middle-low troposphere (Zhang et al., 2014). The equation for the K index is the following:

$$K = (T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700}) \quad (1)$$

where K is the K index and T_{850} , T_{700} , and T_{500} are temperatures at 850 hPa, 700 hPa, and 500 hPa, respectively. T_{d850} and T_{d700} are the dew point temperatures at 850 hPa and 700 hPa, respectively. According to the definition of the K index, the larger the K index is, the more unstable the middle-low tropospheric atmosphere is.

Near-surface daily climatological data (including daily average temperature, relative humidity, wind speed and wind direction) during 38 winters from 1980 to 2017 at Beijing station (station number:

54511) were acquired from the National Meteorological Information Centre (<http://data.cma.cn/site/index.html>). These data were used to construct a relation between circulation type and local meteorological conditions. The location of Beijing station is shown in Fig. 1.

2.2. Air quality data

Haze is mainly caused by aerosol pollution in China (Zhang et al., 2013). A new 'Ambient air quality standard' was published in 2012 by the Ministry of Environmental Protection and the General Administration of Quality Supervision, Inspection and Quarantine of China. Particulate matter with aerodynamic diameter less than 2.5 µm (PM_{2.5}) was included in the index system for the first time. However, long term continuous observation of PM_{2.5} is few in China. PM_{2.5} concentration was observed and released since 2008 in American Embassy in Beijing (Fig. 1). The data can be downloaded in the web (<http://www.stateair.net/web/post/1/1.html>). The monitoring station, 20 m away from the road, represents urban-traffic type. Considering data integrity, PM_{2.5} concentrations in American Embassy during 8 winters from 2010 to 2017 were used to analyze the impact of circulation type on aerosol concentration. The method of quality control of PM_{2.5} concentration is the same as previous study (He et al., 2017a).

2.3. Haze days

With an increase in humidity, hygroscopic condensation growth occurs on fine particles, which then activate as cloud condensation nuclei and finally convert haze to fog. Visibility, particulate matter and relative humidity are thus three important properties of haze. Because of the absence of long-term particulate matter observation, only days with visibility less than 10 km and relative humidity less than 90% are defined as haze days based on previous studies (Yang et al., 2016). Based on visibility and relative humidity, winter haze days from 1980 to 2017 at Beijing station were obtained from the National Meteorological Information Centre.

Aerosol scattering and absorption of solar radiation deteriorate atmospheric visibility. Haze pollution is closely related to the loading of aerosol. Time series of average PM_{2.5} concentration and occurrence frequency of haze days are shown in Fig. 2. We also found that relative low PM_{2.5} concentration in 2015 and 2016, but relative high occurrence frequency of haze in these periods. The difference between haze and PM_{2.5} concentration relates to the change of relative humidity or chemical components of PM_{2.5} which affects optical characteristics of aerosol.

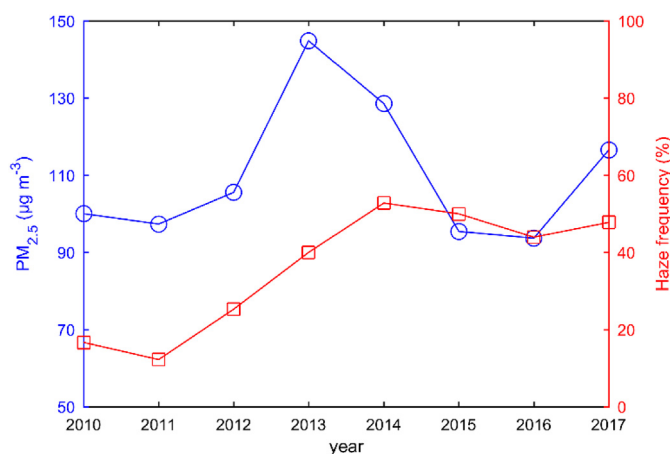


Fig. 2. Time series of average PM_{2.5} concentration and occurrence frequency of haze days during 8 winters from 2010 to 2017.

2.4. Pollutant emissions

Anthropogenic pollutant emissions are important factors affecting haze and air quality. Annual anthropogenic emissions of SO₂, NO_x, and dust from 1999 to 2016 in Beijing and Jing-Jin-Ji area (Beijing municipality, Tianjin municipality and Hebei province, which are the main source region of air pollution in Beijing) were obtained from the China Statistical Yearbook (<http://www.stats.gov.cn/tjsj/ndsj/>) and Beijing Environmental Status Bulletin (<http://www.bjepb.gov.cn/bjhrb/xxgk/ywdt/hjzlk/hjzkgb65/8c3e58b8-1.html>). According to activity level acquired from Multi-resolution emission inventory for China (<http://www.meicmodel.org/>), monthly pollutant emissions were calculated. Winter emissions were acquired based monthly emissions (Fig. 3). Decrease trends of pollutant emissions were found in Beijing during 18 winters from 1999 to 2016 and were significant at the 0.05 level for *t*-test. However, an increase trend of dust emission from 2010 to 2015 were detected in Jing-Jin-Ji area.

2.5. Circulation type classification

Five main circulation classification techniques, i.e., the correlation

method, cluster analysis, principal component analysis (PCA), the fuzzy method, and nonlinear methods, have been frequently used to classify circulation types (Zhang et al., 2012). In this study, the T-mode PCA combined with the K-means cluster was used because previous researchers have proposed that this is the best approach for revealing data structures and effectively identifying circulation types (Huth, 1996). And this method has been widely used in previous studies in China (He et al., 2016a, 2017a, 2017b; Miao et al., 2017; Zhang et al., 2012). Data processing to determine circulation type included five steps. First, three-dimensional ERA SLP grid data (longitude × latitude × time) was reshaped to two-dimensional data (grid × time). Second, data was normalized using z-scores method for time series. Third, the normalized data performed PCA. Fourth, four main components were acquired according to the cumulative variance contribution of 85%. Fifth, the main components were clustered using the K-means cluster, and synoptic-scale circulations were ascertained based on cluster results. The number of clusters depends on the criterion function (Liu and Gao, 2011), and the inflection of the criterion function represents the optimal number of clusters. Finally, the number of clusters was six, and six circulation types were determined (i.e., CT1 to CT6).

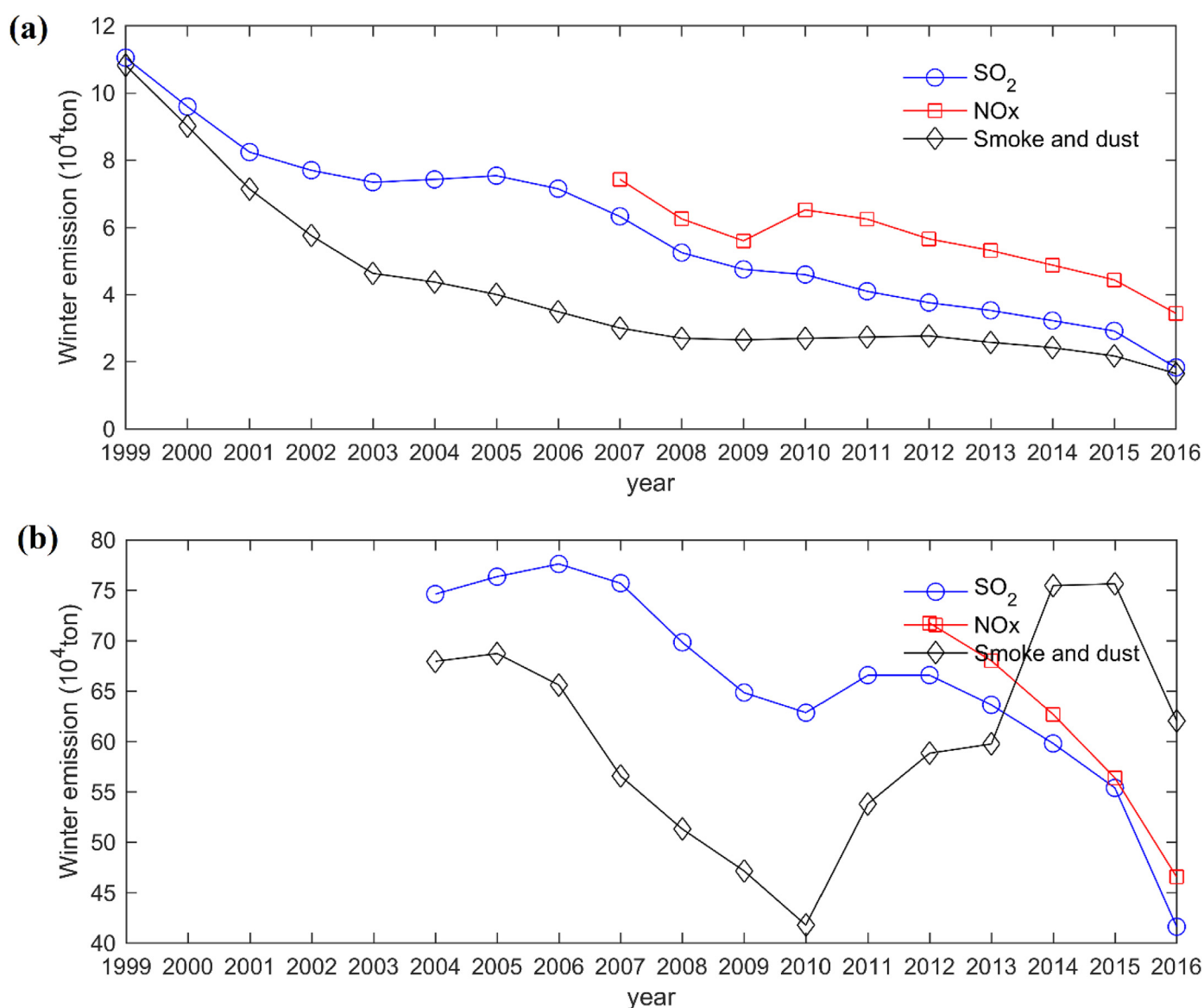


Fig. 3. Pollutant emissions in Beijing (a) and Jing-Jin-Ji (b) during 18 winters from 1999 to 2016.

3. Results and discussion

3.1. Circulation types and weather characteristics

Winter climate characteristics in North China are closely related to the winter monsoon. Previous studies have revealed that a strong winter monsoon is beneficial to pollutant dispersion over Beijing and surrounding regions (Liu et al., 2017). The change of winter circulation types is a direct indicator of winter monsoon intensity. Using the T-mode PCA combined with the K-means cluster, six circulation types are identified. The meteorological fields at each moment are assigned to one circulation type. The mean meteorological fields for six circulation types are calculated. Fig. 4 shows the mean SLP of six circulation types. Fig. 5 shows the spatial distribution of meteorological fields for six circulation types at 1000 hPa. Based on meteorological field characteristics over Beijing and surrounding areas, CT4 and CT5 can be defined as the cold air process, CT3 is defined as weak or degenerate cold air, CT1, CT2 and CT6 are defined as stagnant weather.

According to the spatial distribution of SLP (Fig. 4), CT4 showed the strongest cold air process in North China, with a cold high pressure that reached 1040 hPa and covered Inner Mongolia. Most parts of North China were controlled by northerly winds for CT4. The bottom of high pressure formed an obvious anti-cyclone. A southwest-northeast dry belt was located in the centre of North China and the temperature gradient was large in North China. The cold air process of CT5 was weaker than that of CT4. Compared with CT4, similar weather characteristics for CT5 were found in North China (Fig. 5). CT3 was a degeneration of cold air in North China. The pressure gradient of CT3 was significantly smaller than that of CT4 and CT5. Although the distribution of meteorological fields was similar to that of CT4 and CT5, the wind speed (temperature) decreased (increased) markedly over Beijing. With small pressure gradients, CT1, CT2 and CT6 were typical stagnant weather. For CT1, Beijing was in the back of a weak high-pressure system. Most parts of North China were controlled by southerly and southwesterly wind. The temperature and humidity in Beijing and surrounding regions were affected by warm advection and water vapour transport and were relatively high. For CT2, weak northwesterly wind covered most parts of North China. Wind decreases significantly from northwest of North China to southeast of North China. Spatial distribution of wind was unfavourable for the ventilation capacity over

Beijing. For CT6, a weak low-pressure system existed in Northeast China, and the pressure gradient was very weak in North China. Affected by surface pressure, the northwest region to Beijing was covered by westerly wind, whereas the southeast region to Beijing was covered by southwesterly wind. The change of the wind field formed a convergence zone. Stagnant air resulted in low wind speed over Beijing. Temperatures were high over Beijing because of warm advection (Fig. 5).

The occurrence frequencies for CT1 to CT6 were 16.5%, 19.1%, 20.7%, 14.3%, 16.6%, and 12.8%, respectively. The occurrence frequency of stagnant weather (CT1, CT2 and CT6, 48.4%) was larger than that of cold air (CT4 and CT5, 30.9%) during past 38 winters. The cold air process often occurred in night and morning (02:00 and 08:00, Beijing Time). The evolution of circulation types is an important issue, and there is an evolution between the cold air process and stagnant weather in North China. The frequency of the circulation type at the previous and next moments was calculated, which can be used to infer the evolution of circulation types. When cold air breaks out, the circulation type is CT4 or CT5. With the movement of cold air from the northwest to the southeast, cold air degenerates and the circulation type becomes CT3, followed by CT1, and CT2. After a period of cold air accumulation over Siberia and Outer Mongolia, a new cold air process breaks out, and the circulation type changes from CT2 to CT4 or CT5. Another evolution between CT2 and CT6 is found.

Local meteorological conditions were closely related to synoptic scale circulation types and underlying surface condition. Fig. 6 shows the box graph of surface meteorological parameters at the Beijing meteorological station (Fig. 1) for six circulation types during 38 winters from 1980 to 2017. To be consistent with daily average surface meteorological parameters, a circulation type for one day is defined as a type that appears twice a day or more at four times (08:00, 14:00, 20:00, and 02:00) a day. Circulation types governed local surface meteorological parameters, and meteorological parameters had significant differences for different circulation types based on variance analysis at the 0.05 level (F test). The source of cold high pressure was in Outer Mongolia and Siberia. The cold air process brought a significant decrease of temperature and humidity over Beijing. The cold air process resulted in a large pressure gradient and brought high winds over Beijing. The predominant direction in surface was northerly and northwesterly wind for CT4 and CT5 respectively (Fig. 7). Winter cold

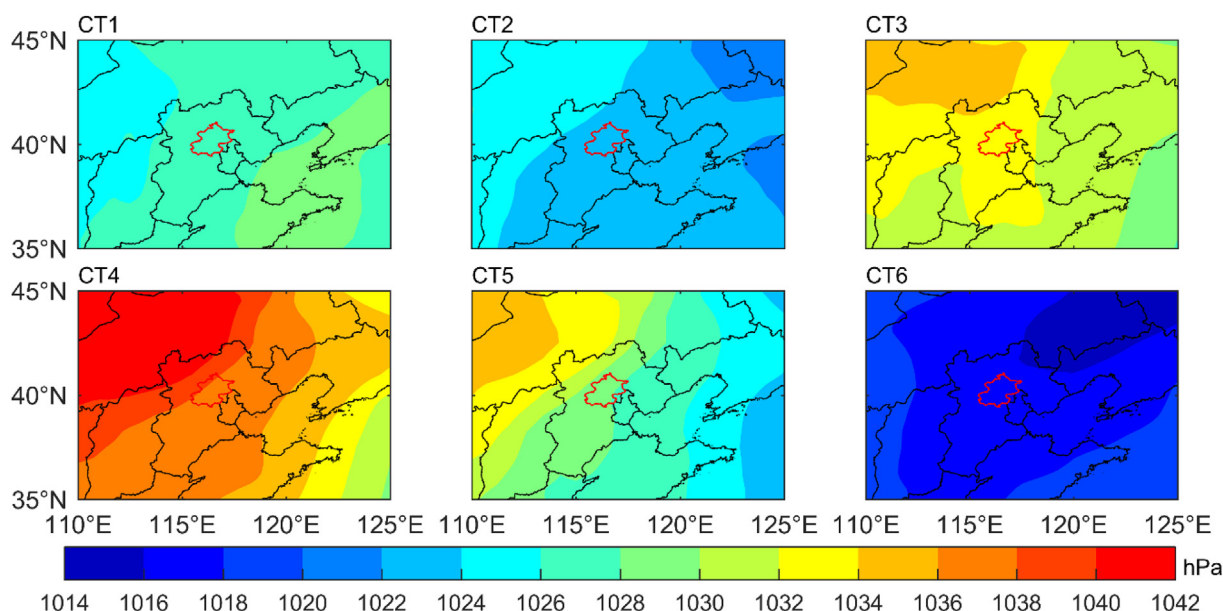


Fig. 4. Mean sea level pressure of six circulation types during 38 winters from 1980 to 2017. Red line represents the boundary of Beijing. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

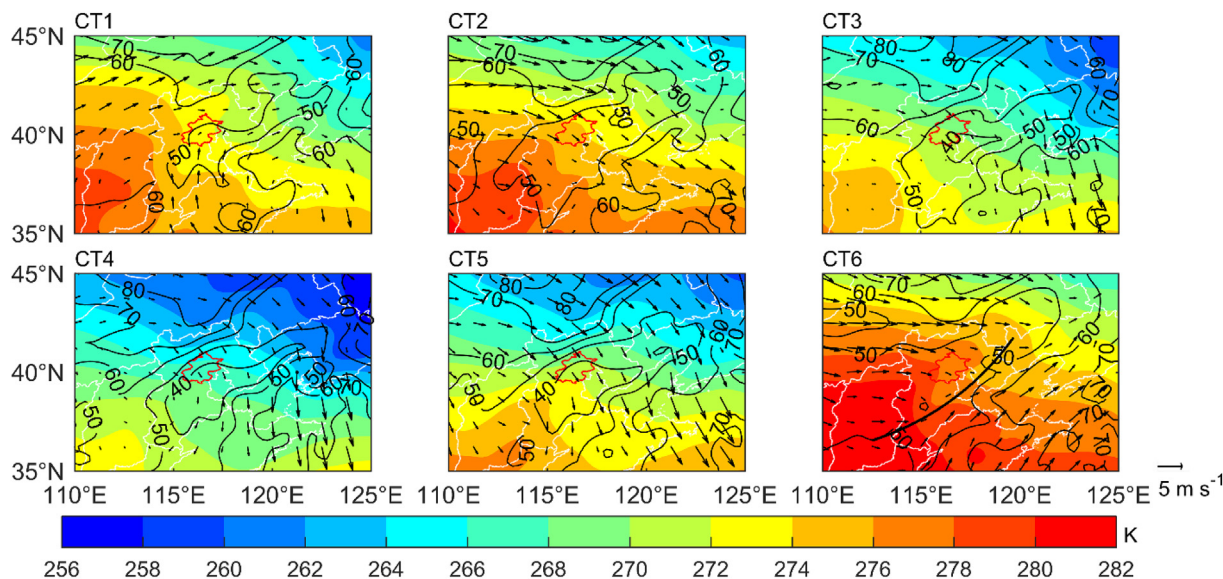


Fig. 5. Mean temperature (shade), relative humidity (contour line), and wind field (arrow) of six circulation types at 1000 hPa during 38 winters from 1980 to 2017. Black line and red line represent convergence line and the boundary of Beijing, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

high pressure in East Asia is a relatively shallow weather system, and the average thickness of cold high pressure is no more than 3 km (Zhang and Chen, 1999). The cold air process decreased low level temperature and the K index and resulted in stable atmospheric stratification in the middle-low troposphere (upper boundary layer). For stagnant weather, the local meteorological parameters were contrary to those for the cold air process, i.e., 2-m temperature, 2-m relative humidity and K index were large, whereas the 10-m wind speed was small in Beijing. The

predominant direction in surface was southwesterly wind (Fig. 7). Northwestern wind was a second prevailing wind for CT2 and CT6. It is interesting that atmospheric stratification in the middle-low troposphere was more stable for the cold air process than for stagnant weather based on the comparison of the K index. For degeneration of cold air, the local meteorological parameters were between the cold air and stagnant weather. Northerly, northeasterly, and southwesterly wind were the main wind direction in surface for CT3 (Fig. 7).

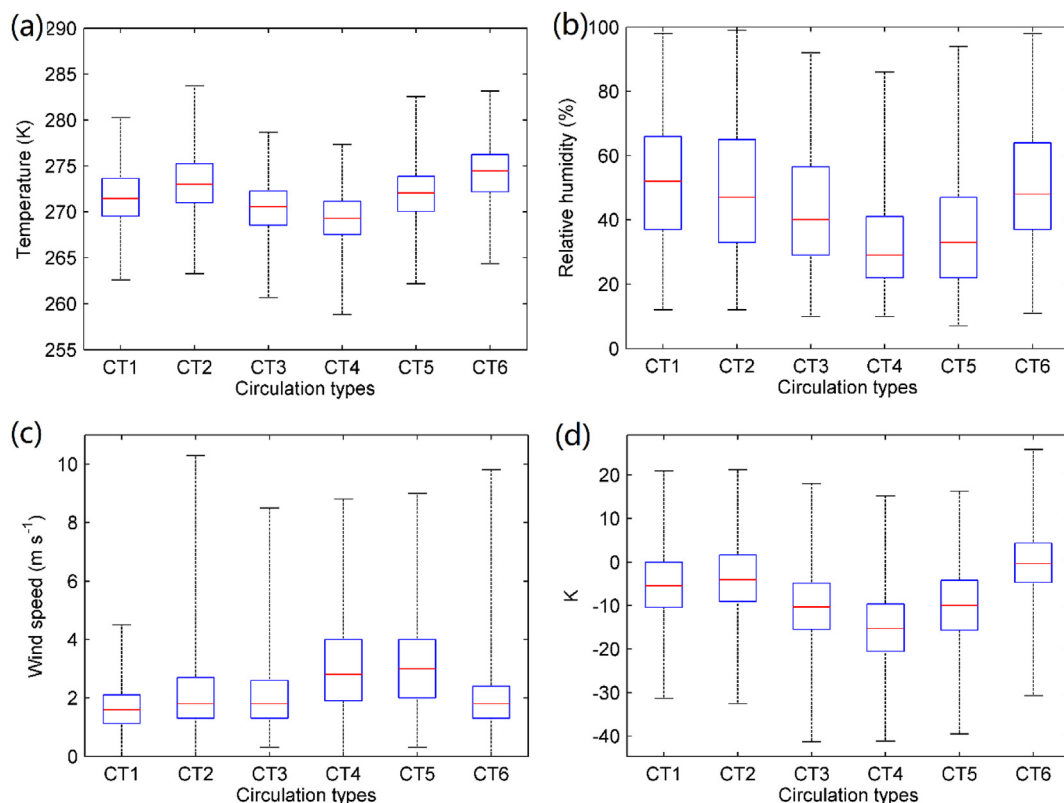


Fig. 6. Box graph of surface pressure (a), 2-m temperature (b), 2-m relative humidity (c) and 10-m wind speed (d) in Beijing for six circulation types during 38 winters from 1980 to 2017.

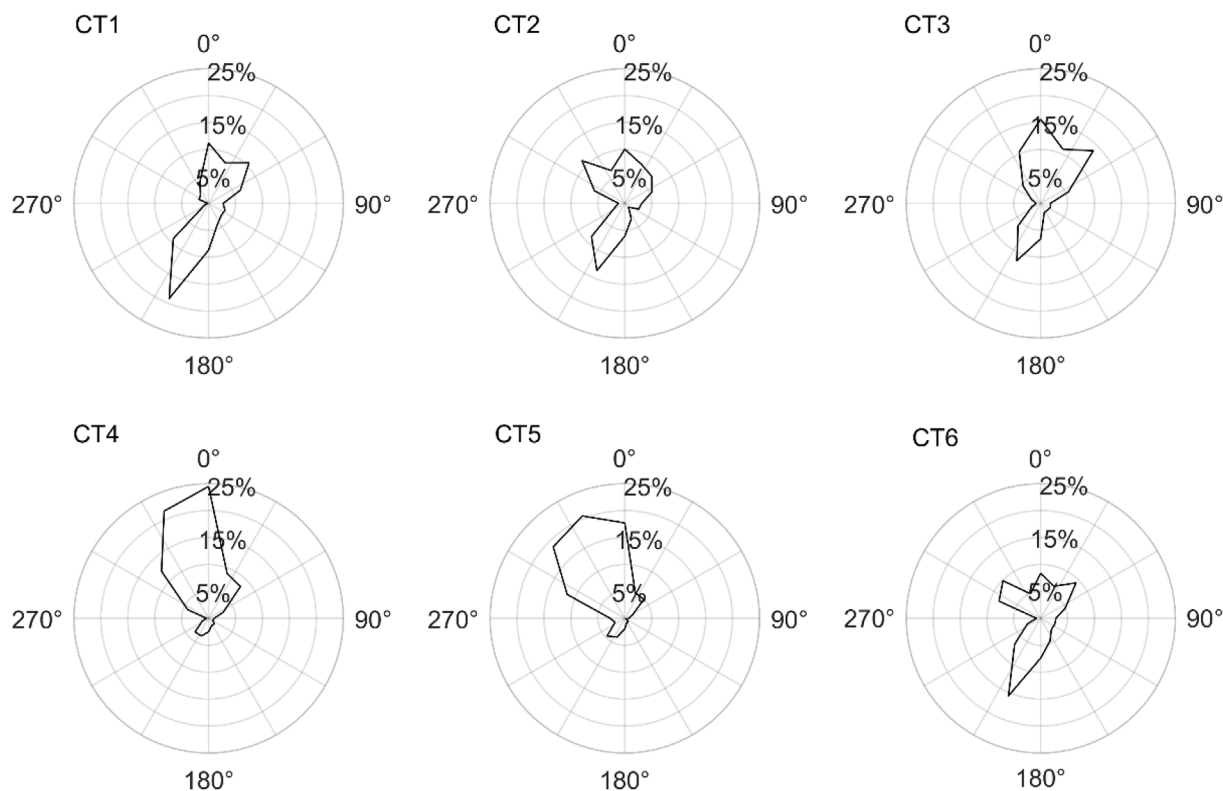


Fig. 7. Wind rose map in Beijing for six circulation types during 38 winters from 1980 to 2017.

Boundary layer structures are also governed by atmospheric circulation (Miao et al., 2017). Fig. 8 shows vertical profiles of potential temperature and wind speed anomaly for six circulation types. The anomaly was defined as the difference between the average value of meteorological parameter for a certain circulation type and the average value during 38 winters from 1980 to 2017. A cold anomaly of potential temperature was detected for CT4 and CT5. Cold anomaly increased with height for CT4 and CT5, which implies that the cold air process increased the atmospheric temperature lapse rate and turbulent mixing in the lower boundary layer by a thermal process and formed a deep mixing layer. A positive anomaly of wind speed was detected for CT4 and CT5, and the positive anomaly increased with height in the boundary layer. This characteristic of vertical profiles of wind speed anomaly for CT4 and CT5 resulted in an increase of vertical wind shear and formed a deep mixing layer by dynamical processes. For stagnant weather, i.e., CT1, CT2, and CT6, an opposite changes of the vertical profiles of potential temperature and wind speed anomaly were found

and formed a shallow mixing layer by thermal and dynamical processes compared with the cold air process (CT4 and CT5). For CT3, potential temperature and wind speed were smaller than the average climatological values in the boundary layer. The anomaly of potential temperature was constant at different heights, whereas the negative anomaly of wind speed increased with height, which restrained the development of turbulence by dynamical processes. In general, the cold air process (stagnant weather) formed a deep (shallow) mixing layer by affecting local atmospheric thermal and dynamical processes. These results did not contradict the K index because of different atmospheric height levels.

In generally, circulation types control pollutant transport characterized by local wind field, atmospheric stability, and boundary layer structure in Beijing. The impacts of circulation types on local meteorology have been widely investigated in other regions. For example, the circulations had two types of control effects on local meteorology indicating: general flow directions and air mass properties; the provision

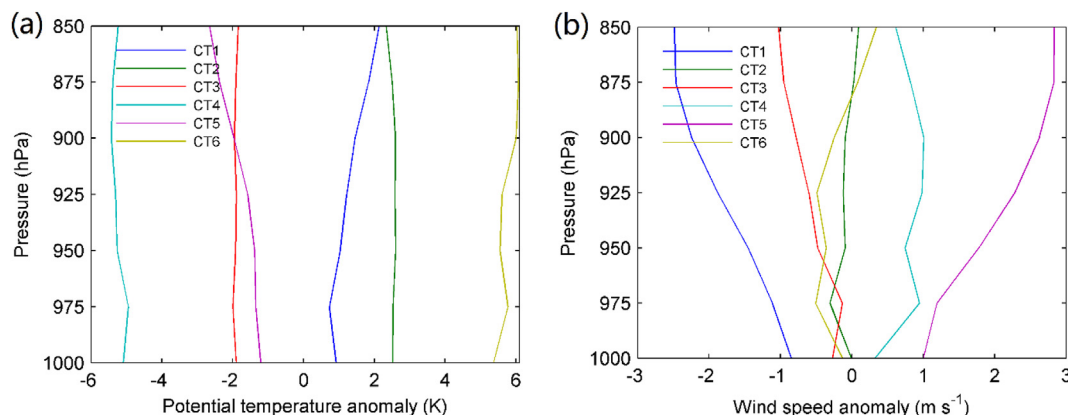


Fig. 8. Vertical profiles of potential temperature anomaly (a) and wind speed anomaly (b) in Beijing for six circulation types during 38 winters from 1980 to 2017.

of the background atmospheric stability and ventilation conditions for Auckland, New Zealand (Jiang et al., 2014). In Hong Kong, synoptic classification could significant distinguish temperature variation at the 0.05 level for F test (Lam and Cheng, 1998). Stagnation weather limited the development of boundary layer, and was associated with slow moving large-scale high pressure system with weak surface pressure gradients and light winds during winter in the Cleveland area, USA (Pasch et al., 2011). Over all, similar impacts have been found.

3.2. Impact of weather type on $PM_{2.5}$ and haze pollution

Atmospheric circulation had an obvious impact on near-surface $PM_{2.5}$ concentration (Fig. 9a). Variance analysis revealed that the different circulation types had significant differences in $PM_{2.5}$ concentration at the 0.05 level (F test). Previous studies revealed that $PM_{2.5}$ concentration was positively correlated with 2-m temperature and 2-m relative humidity and was negatively correlated with 10-m wind speed over the Jing-Jin-Ji area; the correlation passed the *t*-test at the 0.05 level (He et al., 2017a, 2017b; Liu et al., 2017). With low temperature, low relative humidity, and high wind speed, the cold air process (CT4 and CT5) was favourable for pollutant dispersion and brought low $PM_{2.5}$ concentration. After the cold air process (CT3), the atmospheric dispersion capability weakened, and pollutant accumulation resulted in the increase of $PM_{2.5}$ concentration. Stagnant weather (CT1, CT2 and CT6) was accompanied by warmer weather, high humidity and low wind speed, which was unfavourable for pollutant dispersion. For CT1, southwesterly wind transported pollutants from south of Hebei province (He et al., 2017c; Miao et al., 2017) and exacerbated atmospheric pollution over Beijing. A convergence near Beijing for CT6 formed pollutant accumulation. Additionally, the atmospheric stratification in the middle-low troposphere was unstable for stagnant weather (i.e., large K index). Unstable atmospheric stratification favours the formation of cloudy and rainy weather accompanied by high humidity and is conducive to aerosol moisture absorption growth (Zhang et al., 2014). The aerosols in the middle-low troposphere decreased near-surface shortwave radiation and then restrained turbulence development. Mixing layer height is another important factor that affects air pollution (He et al., 2017a). The cold air process (stagnant weather) formed a deep (shallow) mixing layer and enhanced (weakened) the vertical mixing of pollutants, accompanied by low (high) $PM_{2.5}$ concentration.

Table 1 shows the average $PM_{2.5}$ concentration and occurrence frequency of circulation type for each winter from 2010 to 2017. The Chinese Ambient Air Quality Standards (CAAQS) Grade II standards of annual mean $PM_{2.5}$ concentration is $35 \mu\text{g m}^{-3}$. The mean $PM_{2.5}$ concentration in 8 winters in Beijing was 3.2 times of Grade II standards, which implies severe air pollution due to large amount of pollutant emissions. The correlation coefficients between winter average $PM_{2.5}$

concentration and occurrence frequency of six circulation types and cold air were 0.85, 0.71, 0.14, -0.41 , -0.67 , -0.37 , and -0.65 respectively. Based on *t*-test, the correlation coefficients were significant for CT1, CT2 and CT5 at 95% confidence interval. The frequency of cold air was only 25%, 21% and 23% in the winters of 2013, 2014 and 2017, and a stagnant circulation of CT1 exceeded 20% in winter 2013 and 2017, which was adverse for $PM_{2.5}$ transport and dispersion to the outside and facilitated the accumulation of pollutants. The average $PM_{2.5}$ concentration reached $145 \mu\text{g m}^{-3}$, $129 \mu\text{g m}^{-3}$, and $117 \mu\text{g m}^{-3}$ in winter 2013, 2014 and 2017. Although the frequencies of cold air and stagnant weather in winter 2017 were close to that in winter 2013, the $PM_{2.5}$ concentration was significant low in winter 2017 due to great emission control measures. Air pollution is still serious in Beijing even in years with better atmospheric diffusion conditions. The frequency of cold air reached 41% in the winters of 2012 and 2016. However, the average $PM_{2.5}$ concentration was 3.0 and 2.7 times of CAAQS Grade II standards in the winters of 2012 and 2016, respectively. Large amounts of pollutant emissions are the main reason for serious air pollution in the study area (He et al., 2017a).

Correlated with aerosols and visibility, haze is disastrous weather. Similar to the $PM_{2.5}$ analysed above, haze pollution is closely affected by atmospheric circulation (Fig. 9b). A low frequency of haze days was found under cold air processes (i.e., CT4 and CT5), and a high frequency was found for stagnant weather. Fig. 10 shows time series of frequency of haze days and cold air. The average occurrence frequency of haze days for the 38 winters was 37%, with a maximum value of 69% (1990) and a minimum value of 12% (1996). Obvious drop of dust emission was detected in Beijing from 1999 to 2008 (Fig. 3a), which mainly resulted in significant decrease of haze days for same period. Because of obvious pollutant regional transport (He et al., 2017c), a significant increase of dust emission in Jing-Jin-Ji area (Fig. 3b) was responsible for the increase of haze in Beijing after 2010. The fluctuation of pollutant emissions is more stable than that for haze days. These phenomena implicate that meteorological conditions are primary driving for haze interannual variation, and the trend of haze is closely related to the trend of emission in Beijing. The correlation coefficient between the time series of frequency of haze days and cold air frequency during the 38 winters reached -0.41 ($p < 0.1$), which implies that the interannual variation of haze days was closely related to the interannual variation of cold air. In some extreme winters, such as those in 1996, 2008, and 2011, haze days only had 11 days (12.1%), 18 days (19.7%), and 11 days (12.2%) respectively. The occurrence frequency of cold air processes reached 48.4%, 50.5%, and 37.8% for winters in 1996, 2008, and 2011 respectively. The strong cold air improved air quality and decreased the frequency of haze days. Linear regression analysis revealed that winter haze pollution decreased from 1980 to 2017 ($1.5\% \text{ yr}^{-10}$), whereas the frequency of cold air slightly increased

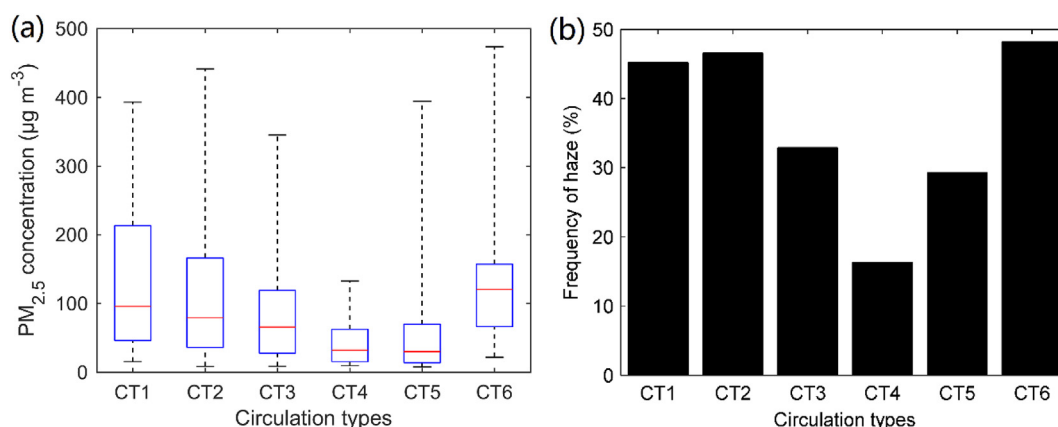


Fig. 9. Box graph of daily mean $PM_{2.5}$ concentration (a) during 8 winters from 2010 to 2017 and occurrence frequency of haze days (b) during 38 winters from 1980 to 2017 for six circulation types.

Table 1PM_{2.5} concentration (mean and standard deviation, $\mu\text{g m}^{-3}$) and occurrence frequency of circulation type (%) for each winters from 2010 to 2017.

	2010	2011	2012	2013	2014	2015	2016	2017
PM _{2.5} concentration	100 ± 74	97 ± 103	106 ± 90	145 ± 117	129 ± 107	95 ± 79	94 ± 106	117 ± 108
Frequency of CT1	15	10	12	29	16	14	13	22
Frequency of CT2	18	16	16	20	19	15	16	23
Frequency of CT3	20	13	27	18	27	23	20	25
Frequency of CT4	13	21	22	11	11	9	18	8
Frequency of CT5	15	14	19	14	9	21	23	15
Frequency of CT6	20	25	4	8	17	17	10	8
Frequency of cold air	27	35	41	25	21	30	41	23

(0.5% yr⁻¹⁰). The decreased trend of haze may have been partly caused by the increased trend of cold air. However, the trend of interannual variation of winter haze and cold air was not significant at the 0.05 level for *t*-test. Artificial measurement of atmospheric visibility (i.e., visibility was subjectively defined by eye based on a reference) has been progressively replaced by automatic measurement since 2011. The bias between artificial measurement and automatic measurement of atmospheric visibility has introduced some uncertainty for haze pollution. Yang et al. (2016) investigated winter haze over eastern China from 1980 to 2014 and found that haze days increased from 21 days in 1980 to 42 days in 2014. The annual haze increased from 1995 to 2012 in North China (Chen and Wang, 2015). The trend of haze days in this paper is different from those in Yang et al. (2016) and Chen and Wang (2015), partly because of the different study areas and seasons considered. Significant regional difference of the trends of haze days was also detected in Hebei province (Fu et al., 2014). And the trends of haze pollution was even different from nearby Hebei province, which implies that haze pollution and interannual trends have obvious local characteristics due to local meteorology and local emissions.

4. Summary and conclusion

Pollutant emissions and meteorological conditions are two key factors that determine haze pollution. Synoptic scale atmospheric circulation governs local meteorological values and the boundary layer and then affects local air quality. Using observations of PM_{2.5} concentrations, haze days based on visibility and relative humidity, meteorological observations and reanalysis data, this paper investigated winter atmospheric circulation types, their relationship with local meteorological conditions and haze pollution over Beijing.

Six circulation types were identified that could significantly distinguish the cold air process, a degeneration of cold air, and stagnant weather. The evolution of atmospheric circulation was also analysed. For the cold air process, a large pressure gradient was found in North China with cold high pressure located northwest of North China, accompanied by low temperature, high relative humidity, and large northwesterly wind over Beijing. Temperatures and wind speed anomalies for cold air in the boundary layer implied that strong turbulence triggered by thermal and dynamical processes formed a deep mixing layer. However, the analysis of the K index revealed that stable atmospheric stratification in the middle-low troposphere (the upper boundary layer) was detected for the cold air process. Cold air facilitated pollutant dispersion and transport to the outside (such as East China, Bohai Sea, and Yellow Sea), and low PM_{2.5} concentration and low frequency of haze days were detected for this circulation type. For stagnant weather, the pressure gradient was very small in North China. The weather was calm, with a relatively warm, low relative humidity, small southwesterly wind, and shallow mixing layer depth. Based on an analysis of the K index, atmospheric stratification was unstable in the middle-low troposphere (the upper boundary layer) compared with the cold air process. A convergence line was found surrounding Beijing, and southerly winds brought pollutants from Hebei province. Stagnant weather was adverse for pollutant dispersion and transport and easily facilitated the accumulation of pollution in Beijing. For the degeneration of cold air, the local meteorological conditions and haze pollution were between those of previous circulation types.

Winter monsoon (or atmospheric circulation) is an important factor determining local meteorological conditions and atmospheric environment in Beijing. The interannual variations of PM_{2.5} concentration and haze days were significantly affected by the variation of atmospheric

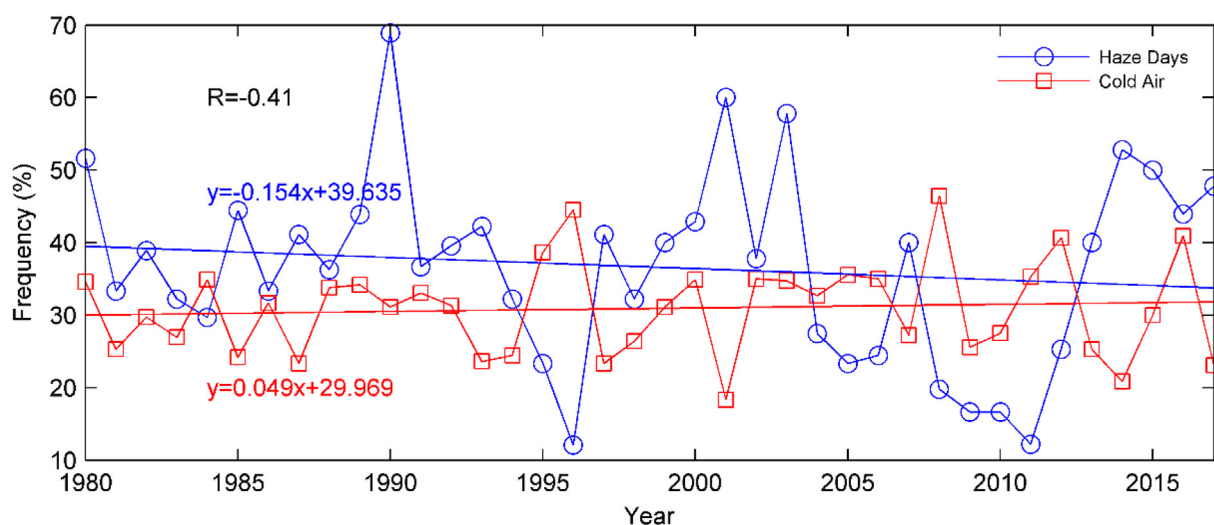


Fig. 10. Time series of occurrence frequency of haze days and cold air during 38 winters from 1980 to 2017. The blue and red lines represent the liner regression trend for haze days and cold air, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

circulation. PM_{2.5} observations revealed that PM_{2.5} pollution was severe in the winters of 2013, 2014 and 2017, which was caused by low frequency of cold air and high frequency of stagnant weather. Air pollution was still serious in Beijing even in years with better atmospheric diffusion conditions (such as winters in 2012 and 2016) because of large amounts of pollutant emissions. The average occurrence frequency of haze days for the 38 winters reached 37%. The high frequency of stagnant weather (48.4%) was one of another reason for the haze pollution. The frequency of haze days was negatively correlated with the frequency of cold air, with a correlation coefficient of -0.41 ($p < 0.1$). The regression analysis of haze days and cold air frequency revealed that the trend of haze days (cold air frequency) decreased (increased) during 38 winters from 1980 to 2017. However, these trends were not significant at the 0.05 level for t -test. Quantifying the relation between atmospheric circulation and haze pollution is very useful for atmospheric environment prediction, understanding the mechanism of haze formation, and air pollution control.

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